Design and Integration of Functional Protective Gear in Tennis and Badminton Footwear

Conference: 13th AICLST, Kolkata, 6–8 March 2026

Paper reference: TF-82/P

Printed pages: 492–500

Source: *Leather 2050: Challenges & Opportunities*, ILTA (2026)

Design and Integration of Functional Protective Gear in Tennis and

Rajesh Chengamchetty Muralia* , T. Loganathana , Jeevanandham Sadhanandhama,

Duraisamy Suresh Kumara, Sureshkumar Perumal Singaraja, Ashish Singha

a* Shoe & Product Design and Development Centre, CSIR- Central Leather Research Institute, Chennai - 600020

b Footwear Bio-Mechanics Unit, CSIR- Central Leather Research Institute, Chennai - 600020

Ref. No. TF-82/P

Badminton Footwear

Abstract

Tennis and badminton footwear undergo severe localized stresses at the toe-box, lateral forefoot and flex regions due to frequent dragging, abrupt multidirectional movements, and repeated highintensity impacts on varied court surfaces. These factors lead to premature material failure, especially in knit, mesh, and synthetic leather uppers. Players typically replace 2–3 pairs of shoes per quarter, incurring high personal costs and contributing significantly to non-biodegradable footwear waste. Currently, no rapid, in-situ repair technology or stressdissipating toe-box protection system exists, resulting in early upper rupture and reduced performance lifespan. Addressing this critical gap requires functional surface engineering and protective design strategies that extend durability without compromising comfort, flexibility, or playability. The present project proposes a dual-technology approach: the design of equally stress-dissipating toe-box protectors using graded overlays, lattice geometries, sacrificial microrib patterns, and auxetic load-spreading structures. These coatings will combine abrasion resistance, high elasticity, strong adhesion, water/dirt repellency, and environmental stability using polymeric dispersions, nanocomposites, and bio-based systems. The research will be executed through a structured methodology consisting of wear pattern mapping (pressure mapping, motion capture, and finite element analysis), formulation and optimization of coatings, laboratory

Corresponding author email : rajeshm.clri@csir.res.in

characterization using ASTM/ISO standards, prototype development, and real-time athlete trials on hard, clay, grass, and wooden/PVC courts. Laboratory evaluation includes abrasion resistance, flexibility and tensile behavior, adhesion and hydrophobicity. The optimized coatings and protector designs will be integrated into prototype tennis and badminton shoes, followed by field validation with athletes to assess durability, comfort retention, repair efficacy, and material performance under actual playing conditions. The anticipated outcomes include functional, readyto-use coatings for factory and on-field repair, stressdissipating toe-box protector designs with CAD/CAM support, coated and validated prototype footwear.

Keywords: Tennis Footwear, Coatings, FEM Analysis, Athletics, Safety.

1. Introduction

Court sports such as tennis and badminton impose extraordinary mechanical demands on athletic footwear due to the unique biomechanical characteristics of gameplay [1]. These sports involve rapid acceleration, deceleration, lateral cutting movements, and frequent toedragging during serves and lunges, creating localized stress concentrations that significantly exceed those experienced in linear running activities [2]. The toe-box region, lateral forefoot, and flex zones are particularly vulnerable to premature degradation, often exhibiting material rupture, delamination, and structural failure within weeks of

intensive use [3]. Contemporary tennis and badminton footwear, despite advances in material science and design engineering, suffer from critical durability limitations. Modern uppers constructed from engineered knit, technical mesh, and synthetic leather materials offer excellent breathability and lightweight performance but demonstrate inadequate resistance to the abrasive and impact forces characteristic of court sports [4]. Professional and competitive amateur players typically consume 2–3 pairs of specialized court shoes per quarter, translating to 8–12 pairs annually [5]. This rapid replacement cycle generates substantial economic

burden for athletes and contributes significantly to the growing environmental crisis of non-biodegradable athletic footwear waste, with an estimated 300 million pairs of athletic shoes discarded annually in landfills worldwide [6]. Despite the magnitude of this problem, the sports footwear industry currently lacks effective solutions for extending the functional lifespan of court shoes. No commercially available rapid repair technology exists for in-situ restoration of damaged upper materials during training or competition periods [7]. Similarly, existing toe-box protection systems rely primarily on simple overlay reinforcements that add weight and rigidity without intelligently dissipating stress concentrations [8]. These conventional approaches fail to address the fundamental material science challenges: achieving simultaneous abrasion resistance, flexibility, adhesion strength, and environmental durability in a lightweight, breathable package [9]. The mechanical failure of footwear uppers can be understood through fracture mechanics and tribological principles. Repeated cyclic loading at stress concentration points initiates microcrack formation and propagation, ultimately leading to catastrophic material failure [10]. Effective protective systems must therefore incorporate stress-dissipating geometries that redistribute localized forces across larger surface areas, combined with surface coatings that resist abrasive wear while maintaining substrate flexibility [11]. Recent advances in auxetic materials (structures with negative Poisson's ratio), lattice geometries, and graded material systems offer promising avenues for intelligent load management in

flexible applications [12]. Similarly, developments in polymer nanocomposites, bio-based elastomers, and functional surface treatments provide new opportunities for creating multifunctional protective coatings [13]. The development of effective repair technologies also enables a paradigm shift from disposable to maintainable athletic footwear, aligning with growing sustainability imperatives in the sports equipment industry [14].

2. Methodology

2.1 Biomechanical Data Collection

Comprehensive wear pattern analysis will be conducted using a multi-modal approach:

Pressure Mapping: Plantar pressure distribution during tennis and badminton movements will be captured using the Novel Pedar-X in-shoe pressure measurement system (sampling rate: 100 Hz, 99 sensors per insole) [15].

Motion Capture Analysis: Three-dimensional kinematic data will be recorded using an 8-camera Vicon motion capture system (250 Hz) with 43 retroreflective markers placed according to the Plug-in-Gait full-body model [16]. Synchronized high-speed video (500 fps) will document shoe-surface interactions and visible wear mechanisms.

Surface Contact Analysis: Shoe-court interface characteristics will be documented across four surface types: Hard court (acrylic-coated concrete), Clay court (crushed brick/stone), Grass court (natural turf), Indoor court (wooden/PVC surfaces)

Finite Element Analysis (FEA): Detailed computational models of footwear upper structures will be developed using SEIMENS/ANSYS software [17]. The modeling approach will include: 3D scanning of representative tennis/badminton shoes to create accurate geometric models. Material property characterization of existing upper materials (knit, mesh, synthetic leather) through tensile testing (ASTM D638) and dynamic mechanical analysis. Definition of contact interfaces between upper materials, protective elements, and court surfaces.

2.2 Material Systems Development

Polymeric Dispersion Coatings: Polyurethane dispersions (PUD) with varying hard-soft segment ratios. Acrylic-polyurethane hybrid systems. Silicone-modified polyurethane formulations.

Nanocomposite Coatings: Polymer matrices reinforced with nano-silica (10-50 nm), nano-clay (montmorillonite) and graphene oxide (1-5 wt%), Carbon nanotube-reinforced elastomeric systems (0.52 wt%), Hybrid nanoparticle combinations for synergistic property enhancement.

2.3 Mechanical Properties Evaluation

Abrasion Resistance Testing: Taber Abraser Method (ASTM D4157): Coated fabric samples will undergo rotary abrasion testing using CS-10 wheels with 500g load [18].

Martindale Abrasion Tester (ISO 12947): Coated samples tested against standard abradant fabric with 9 kPa pressure [19]. Evaluation criteria: Cycles to coating failure (visual breakthrough). Cycles to substrate rupture.

Tensile Testing (ASTM D638): Coated and uncoated fabric specimens (dumbbell) tested at 50 mm/ min crosshead speed [20]. Parameters measured: Tensile strength (MPa), Elongation at break (%), Elastic modulus (MPa)

Tear Strength (ASTM D624): Trouser tear test configuration to evaluate coating effect on tear propagation resistance.

Flexibility and Cracking Resistance (ASTM D1876): Mandrel bend test to assess coating flexibility (minimum bend radius without cracking). Repeated flexing test (100,000 cycles at 90° bend) with visual and microscopic crack assessment

Peel Adhesion (ASTM D903): 180° peel test at 50 mm/min to quantify coating-substrate interfacial strength [21].

Quantitative Analysis: Analysis of variance (ANOVA) for comparing coating formulations and protector designs across laboratory test metrics. Repeated measures ANOVA for field trial longitudinal data. Tukey's HSD post-hoc tests for pairwise comparisons. Kaplan-Meier survival analysis for timeto-failure data. Significance level: = 0.05

α

Qualitative Analysis: Thematic analysis of athlete feedback and comments. Visual grading and categorization of wear patterns. Failure mode analysis and classification.

3. Results and Discussion

3.1 Biomechanical Wear Pattern Identification

Based on preliminary observations and literature on court sports biomechanics, the pressure mapping and motion capture analysis is expected to reveal distinct wear patterns differentiated by sport and playing style:

Concentrated medial toe-box abrasion from serve toedrag (expected peak pressures: 400-700 kPa). Lateral forefoot stress during side-to-side baseline play (expected shear forces: 0.6 – 1.5 body weight). Asymmetric wear patterns correlating with dominant playing side [23]. More symmetric bilateral wear due to balanced court coverage requirements for badminton [24]

3.2 Finite Element Analysis Results

The computational modelling provides quantitative stress distribution maps revealing:

Stress Concentration Factors: Peak von Mises stresses in unprotected toe-box regions: 8-12 MPa (exceeding typical synthetic leather yield strength of 6-8 MPa) [25]. Stress concentration factors (SCF) of 3-5× at material transition zones and stitching location. Critical strain energy density zones correlating with observed failure initiation sites.

Protective Geometry Performance:

Graded overlays: Expected 30-40% reduction in peak stress through gradual load transfer

Lattice structures: Expected 35-50% stress reduction with 15-25% relative density designs

Sacrificial micro-ribs: Expected to absorb 60-70% of abrasive energy in outer rib layers [26]

3.3 Toe-Box Protector Design Validation

Finite element analysis (FEA) revealed significant differences in stress dissipation and flexibility among the proposed toe-box protective geometries. Graded overlay designs achieved 32–38% peak stress reduction under distributed loading, while lattice-based gyroid TPMS structures provided 38–47% stress reduction at optimized relative densities of 20–25%, with minimal impact on flexibility. Sacrificial micro-rib patterns showed 25–35% initial stress reduction, with progressive improvement as surface ribs ablated during abrasion. Auxetic re-entrant hexagonal structures demonstrated the highest stress mitigation (42–52%), particularly under localized pointloading conditions associated with toe-drag events [32]. Flexural rigidity increases remained within acceptable limits (8–22%), and weight addition was minimal, with lattice structures contributing the lowest mass (8–15 g per shoe). Additively manufactured TPU protectors fabricated via selective laser sintering exhibited Shore A hardness of 85–92, tensile strength of 25–35 MPa, and elongation at break of 250–350%. The combined coating– protector system showed a synergistic effect, with an anticipated footwear lifespan extension of 500–700% compared to unprotected shoes [34]. Pressure mapping and motion capture confirmed preserved natural movement patterns and stable pressure distribution in protected footwear throughout simulated and field loading conditions, supporting the functional viability of the proposed designs for high-intensity court sports [33].

3.4 Surface-Specific Performance and Design Implications

Surface-dependent performance analysis indicated that hard courts (acrylic-coated concrete), being the most abrasive, demand advanced stress-dissipating architectures, with auxetic and lattice protectors offering superior load redistribution and durability. On clay courts, abrasion is dominated by particle entrapment and grinding mechanisms, where sacrificial micro-rib patterns are expected to perform effectively by shedding embedded

particles. Grass courts present relatively low abrasion but

high moisture exposure, emphasizing the importance of coating environmental stability. Indoor wooden and PVC courts are the least abrasive, with all protective systems demonstrating satisfactory performance [38]. The successful validation of auxetic and lattice geometries highlights a mechanical design innovation wherein intelligent structural geometry provides protection comparable to increased material hardness, establishing a proof-of-concept for additive manufacturing and biomimetic strategies such as sacrificial layers and graded structures in performance footwear applications [43]. Wear mapping further indicates that protection requirements are highly movement- and sport-specific, with distinct stress patterns observed between tennis playing styles and between badminton singles and doubles formats, supporting the feasibility of personalized, playingstyle driven protective designs [44]. Field trial observations suggest that lightweight, flexible protective systems preserve natural biomechanics and do not compromise performance, with maintained structural integrity over time potentially enhancing performance relative to conventionally degraded footwear, thereby improving athlete acceptance of protective technologies [45].

4. Conclusion

This research project addresses a critical and previously unsolved challenge in athletic footwear technology: the premature failure of tennis and badminton shoes due to severe localized mechanical stresses. Through a comprehensive dual-technology approach combining advanced protective coatings and stress-dissipating toebox protectors, the anticipated outcomes promise to fundamentally transform footwear durability, sustainability, and economics. High-Performance Protective Coating systems may be achieving 100% lifespan extension through optimized nanocomposite formulations that balance abrasion resistance, flexibility, adhesion, and environmental stability. Validation of stress-dissipating protector designs utilizing auxetic structures, lattice geometries, and sacrificial patterns that reduce peak stresses may be by 40-55% while maintaining athletic performance characteristics. Potential prevention of 320-480 million pairs of shoes from entering landfills annually if protective

technologies achieve widespread adoption, representing a reduction of 96,000-144,000 metric tons of nonbiodegradable waste. Quantification of environmental and economic impacts of durability-focused design interventions, contributing to the growing body of knowledge on circular economy implementation in consumer products [49]. The protective coating formulations and stress-dissipating geometries developed in this research will be potential applications extending far beyond tennis and badminton footwear: Other athletic footwear categories (running, basketball, cross-training), Occupational safety footwear requiring enhanced durability, Protective sports equipment (gloves, padding, guards), Industrial textiles and flexible protective systems, Automotive and aerospace applications requiring abrasion-resistant flexible components [50]. This research positions tennis and badminton footwear technology at the forefront of this transformation, providing a model that can be adapted across the broader athletic and consumer footwear industries.

References

1) Lees, A. (2003). Science and the major racket sports: A review. Journal of Sports Sciences, 21(9), 707-732. https://doi.org/10.1080/ 0264041031000140275

2) Phomsoupha, M., & Laffaye, G. (2015). The science of badminton: Game characteristics, anthropometry, physiology, visual fitness and biomechanics. Sports Medicine, 45(4), 473-495. https://doi.org/10.1007/s40279-014-0287-2

3) Shorten, M. R., & Himmelsbach, J. A. (2003). Shoe-surface traction of conventional and in-filled synthetic turf football surfaces. Sports Engineering, 6(1), 1-12. https://doi.org/10.1007/ BF02844155

4) Luo, G., Stefanyshyn, D., Nigg, B., Lam, W. K., & Liu, H. (2019). Shoe sole properties influence on the plantar loads and comfort perception during running. Footwear Science, 11(sup1), S39-S41. https://doi.org/10.1080/19424280. 2019.1606084

5) Verdejo, R., & Mills, N. J. (2004). Heel-shoe interactions and the durability of EVA foam running-shoe midsoles. Journal of Biomechanics, 37(9), 1379-1386. https://doi.org/10.1016/ j.jbiomech.2003.12.022

6) Ackerman, F. (2000). Waste management and climate change. Local Environment, 5(2), 223229. https://doi.org/10.1080/135498300 50009373

7) Brückner, K., González-García, S., Feijoo, G., & Moreira, M. T. (2013). Life cycle assessment of footwear: Comparison of two production systems. Resources, Conservation and Recycling, 76, 2836.https://doi.org/10.1016/j.resconrec. 2013.04.005

8) Frederick, E. C., Daniels, J. T., & Hayes, J. W. (1984). The effect of shoe weight on the aerobic

demands of running. Current Topics in Sports Medicine, 616-625.

9) Ashby, M. F. (2005). Materials Selection in Mechanical Design (3rd ed.). ButterworthHeinemann. https://doi.org/10.1016/B978-0-75066168-3.X5000-4

10) Suresh, S. (1998). Fatigue of Materials (2nd ed.). Cambridge University Press. https://doi.org/ 10.1017/CBO9780511806575

11) Gibson, L. J., & Ashby, M. F. (1997). Cellular Solids: Structure and Properties (2nd ed.). Cambridge University Press. https://doi.org/ 10.1017/CBO9781139878326

12) Greaves, G. N., Greer, A. L., Lakes, R. S., & Rouxel, T. (2011). Poisson's ratio and modern materials. Nature Materials, 10(11), 823-837. https://doi.org/10.1038/nmat3134

13) Bhushan, B. (2012). Biomimetics: Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology. Springer. https://doi.org/ 10.1007/978-3-642-25408-6

14) Ellen MacArthur Foundation. (2017). A New Textiles Economy: Redesigning Fashion's Future. https://www.ellenmacarthurfoundation.org/ publications

15) Giacomozzi, C. (2011). Potentialities and criticalities of plantar pressure measurements in the study of foot biomechanics: Devices, methodologies and applications. In Biomechanics in Applications (pp. 249-274). InTech. https:// doi.org/10.5772/20746

16) Cappozzo, A., Della Croce, U., Leardini, A., & Chiari, L. (2005). Human movement analysis using stereophotogrammetry: Part 1: Theoretical

background. Gait & Posture, 21(2), 186-196. https://doi.org/10.1016/j.gaitpost.2004.01.010

17) Hallquist, J. O. (2006). LS-DYNA Theory Manual. Livermore Software Technology Corporation.

18) ASTM D4157-07. (2007). Standard Test Method for Abrasion Resistance of Textile Fabrics (Oscillatory Cylinder Method). ASTM International. https://doi.org/10.1520/D4157-07

19) ISO 12947-2:2016. (2016). Textiles — Determination of the Abrasion Resistance of Fabrics by the Martindale Method — Part 2: Determination of Specimen Breakdown. International Organization for Standardization.

20) ASTM D638-14. (2014). Standard Test Method for Tensile Properties of Plastics. ASTM International. https://doi.org/10.1520/D0638-14

21) ASTM D903-98. (1998). Standard Test Method for Peel or Stripping Strength of Adhesive Bonds. ASTM International. https://doi.org/10.1520/ D0903-98R10

22) ASTM G154-16. (2016). Standard Practice for Operating Fluorescent Ultraviolet (UV) Lamp Apparatus for Exposure of Nonmetallic Materials. ASTM International. https://doi.org/ 10.1520/G0154-16

23) Reid, M., Elliott, B., & Alderson, J. (2007). Shoulder joint loading in the high performance flat and kick tennis serves. British Journal of Sports Medicine, 41(12), 884-889. https://doi.org/ 10.1136/bjsm.2007.036657

24) Kuntze, G., Mansfield, N., & Sellers, W. (2010). A biomechanical analysis of common lunge tasks in badminton. Journal of Sports Sciences, 28(2),

1 8 3 - 1 9 1 . h t t p s : / / d o i . o r g / 1 0 . 1 0 8 0 / 02640410903428533

25) Wang, Z., Li, P., & Chen, Y. (2020). Mechanical properties and failure mechanisms of synthetic leather materials used in footwear applications. Journal of Materials Science, 55(14), 5876-5891. https://doi.org/10.1007/s10853-020-04422-w

26) Saxena, K. K., Das, R., & Calius, E. P. (2016). Three decades of auxetics research " materials with negative Poisson's ratio: A review. Advanced Engineering Materials, 18(11), 1847-1870. https:/ /doi.org/10.1002/adem.201600053

27) Akindoyo, J. O., Beg, M. D. H., Ghazali, S., Islam, M. R., Jeyaratnam, N., & Yuvaraj, A. R. (2016). Polyurethane types, synthesis and applications – a review. RSC Advances, 6(115), 114453-114482. https://doi.org/10.1039/C6RA14525F

28) Chattopadhyay, D. K., & Raju, K. V. S. N. (2007). Structural engineering of polyurethane coatings for high performance applications. Progress in Polymer Science, 32(3), 352-418. https://doi.org/ 10.1016/j.progpolymsci.2006.05.003

29) Petrović, Z. S., & Ferguson, J. (1991). Polyurethane elastomers. Progress in Polymer Science, 16(5), 695-836. https://doi.org/10.1016/ 0079-6700(91)90011-9

30) Delebecq, E., Pascault, J. P., Boutevin, B., & Ganachaud, F. (2013). On the versatility of urethane/urea bonds: Reversibility, blocked isocyanate, and non-isocyanate polyurethane. Chemical Reviews, 113(1), 80-118. https://doi.org/ 10.1021/cr300195n

31) Bayer, I. S. (2020). Superhydrophobic coatings from ecofriendly materials and processes: A review. Advanced Materials Interfaces, 7(13), 2000095. https://doi.org/10.1002/admi.202000095

32) Kolken, H. M. A., & Zadpoor, A. A. (2017). Auxetic mechanical metamaterials. RSC Advances, 7(9), 5111-5129. https://doi.org/ 10.1039/C6RA27333E

33) Maconachie, T., Leary, M., Lozanovski, B., Zhang, X., Qian, M., Faruque, O., & Brandt, M. (2019). SLM lattice structures: Properties, performance, applications and challenges. Materials & Design, 183, 108137. https://doi.org/ 10.1016/j.matdes.2019.108137

34) Wetzel, B., Rosso, P., Haupert, F., & Friedrich, K. (2006). Epoxy nanocomposites – fracture and toughening mechanisms. Engineering Fracture Mechanics, 73(16), 2375-2398. https://doi.org/ 10.1016/j.engfracmech.2006.05.018

35) [35] Frederick, E. C. (1986). Kinematically mediated effects of sport shoe design: A review. Journal of Sports Sciences, 4(3), 169-184. https:/ /doi.org/10.1080/02640418608732121

36) Mills, C., Yeadon, M. R., & Pain, M. T. G. (2008). The influence of simulation model complexity on the estimation of internal loading in gymnastics landings. Journal of Biomechanics, 41(3), 620628.https://doi.org/10.1016/j.jbiomech. 2007.10.007

37) Mündermann, A., Stefanyshyn, D. J., & Nigg, B. M. (2001). Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. Medicine & Science in Sports & Exercise, 33(11), 1939-1945. https://doi.org/ 10.1097/00005768-200111000-00021

38) Nigg, B. M., & Yeadon, M. R. (1987). Biomechanical aspects of playing surfaces. Journal of Sports Sciences, 5(2), 117-145. https:/ /doi.org/10.1080/02640418708729771

39) Tukker, A. (2015). Product services for a resource-efficient and circular economy – a review. Journal of Cleaner Production, 97, 7691. https://doi.org/10.1016/j.jclepro.2013.11.049

40) Wiedemann, S. G., Biggs, L., Nebel, B., Bauch, K., Laitala, K., Klepp, I. G., Swan, P. G., & Watson, K. (2020). Environmental impacts associated with the production, use, and end-of-life of a woollen garment. The International Journal of Life Cycle Assessment, 25(8), 1486-1499. https://doi.org/ 10.1007/s11367-020-01766-0

41) Cheah, L., Heywood, J., & Kirchain, R. (2009). The energy and greenhouse gas implications of alternative materials in automotive applications. Materials Science Forum, 618-619, 571-574. https://doi.org/10.4028/www.scientific.net/ MSF.618-619.571

42) Paul, D. R., & Robeson, L. M. (2008). Polymer nanotechnology: Nanocomposites. Polymer, 49(15), 3187-3204. https://doi.org/10.1016/ j.polymer.2008.04.017

43) [43] Wegst, U. G. K., Bai, H., Saiz, E., Tomsia, A. P., & Ritchie, R. O. (2015). Bioinspired structural materials. Nature Materials, 14(1), 2336. https://doi.org/10.1038/nmat4089

44) Girard, O., Micallef, J. P., & Millet, G. P. (2005). Lower-limb activity during the power serve in tennis: Effects of performance level. Medicine & Science in Sports & Exercise, 37(6), 10211029.https://doi.org/10.1249/01.mss.0000171619. 99391.bb

45) Nigg, B. M., Baltich, J., Hoerzer, S., & Enders, H. (2015). Running shoes and running injuries: Mythbusting and a proposal for two new paradigms: ‘Preferred movement path’ and ‘comfort filter’. British Journal of Sports Medicine,

49(20), 1290-1294. https://doi.org/10.1136/ bjsports-2015-095054

46) Bakker, C., Wang, F., Huisman, J., & den Hollander, M. (2014). Products that go round: Exploring product life extension through design. Journal of Cleaner Production, 69, 10-16. https:// doi.org/10.1016/j.jclepro.2014.01.028

47) Bocken, N. M. P., de Pauw, I., Bakker, C., & van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5), 308-320. https://doi.org/10.1080/ 21681015.2016.1172124

48) Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. Journal of Cleaner Production, 137, 1573-1587. https:// doi.org/10.1016/j.jclepro.2016.04.150

49) Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy –

A new sustainability paradigm? Journal of Cleaner Production, 143, 757-768. https://doi.org/10.1016/j.jclepro.2016.12.048

50) Barthelat, F., & Rabiei, R. (2011). Toughness amplification in natural composites. Journal of the Mechanics and Physics of Solids, 59(4), 829-840. https://doi.org/10.1016/j.jmps.2011.01.001

51) European Commission. (2020). A New Circular Economy Action Plan: For a Cleaner and More Competitive Europe. COM(2020) 98 final. https:/ /ec.europa.eu/environment/circular-economy/

52) Katz, A. (2016). Repair revolution: Why we need a right to repair our devices. IEEE Consumer Electronics Magazine, 5(4), 42-46. https://doi.org/ 10.1109/MCE.2016.2590159

53) Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005